Hydrogen Fuel Cell for High Capacity Buses

Prepared for
Transport Canada
Transportation Development Centre

By
UTDC Research and Development Ltd.

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HYDROGEN FUEL CELL

FOR

HIGH CAPACITY BUSES

FINAL REPORT

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17. Abstract

The project had the objective of developing the conceptual design and preliminary specifications of a hydrogen fuel cell package for a high capacity intercity bus. The subject bus design was a double-deck 14 m long bus largely based on previous work for Transport Canada by others, of fuel efficient design featuring an aluminum structure. An operational requirement was developed. Key elements included a range of 1,000 km, payload of 80 to 100 passengers, plus baggage and freight. Modifications to the baseline diesel bus included deletion of the diesel propulsion package, and addition of a liquid hydrogen storage tank, fuel cell stacks and auxiliaries, D.C. power control unit and D.C. drive motor. The modifications resulted in a 24% tare weight growth which included larger wheels and tires, extra structure and provision for firewalls and safety systems. Top speed, acceleration and range were unaffected, but payload was reduced from 81 to 79 passengers, and some baggage and freight volume was sacrificed. Energy consumption was reduced by one third. The report concludes that the concept is practicable and offers some unique and attractive features, and that future developments in fuel cells would virtually eliminate the lost revenue volume.

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17 Résumé

Ce rapport concerne le projet visant l'étude conceptuelle et la spécification provisoire d'une pile à combustible (hydrogène) pour autocar grande capacité. Le véhicule visé était un autocar à impériale, d'une longueur de 14 m, dont la conception a été pour une large part réalisée sous l'égide de Transport Canada, et se caractérise par une construction en aluminium et un rendement énergétique amélioré. Les paramètres de départ avaient été définis comme suit: autonomie, 1000 km, capacité de 80 à 100 passagers, fret et bagages en plus. La motorisation diesel de ce véhicule a été remplacée par une chaîne cinématique tout électrique à courant continu, un réservoir à hydrogène liquide, une batterie de piles à combustible et ses accessoires et, enfin, une unité de commande à courant continu. Toutes ces modifications ont augmenté le poids à vide en ordre de marche de 24%, mais cela comprend des roues et des pneus plus larges, une charpente renforcée, des cloisons coupe-feu et diverses autres protections. La vitesse maximale, l'accélération et l'autonomie n'ont pas subi le contrecoup de ces changements, mais la capacité a baissée: nombre de passagers ramenés de 81 à 79 et volume des soutes à fret et à bagages quelque peu réduit. Par contre, la consommation a baissée d'un tiers. Le rapport conclut en disant que le concept est réalisable, qu'il possède des caractéristiques uniques et intéressantes et que le perfectionnement de la pile à hydrogène permettrait de rattraper la perte de revenu dû à la baisse de capacité.

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1.0 INTRODUCTION

This report describes work carried out by UTDC R&D Ltd. for Transport Canada's Transportation Development Centre (TCTDC) to develop the conceptual design and preliminary specifications of a hydrogen fuel cell propulsion package for a high-capacity inter-city bus. The overall objectives of the work were to reduce petroleum consumption and improve the operating efficiency of inter-city bus transportation.

The propulsion system studied included a fuel cell using pure electrolytic hydrogen as fuel, supplied from an onboard liquid hydrogen (LH_2) storage system. The electrical energy so produced would be controlled by a power-conditioning unit and fed to a DC motor for generation of tractive effort. The high-capacity inter-city bus that was the focus of the study is a generic double-deck design largely based on a design by Guillon, Smith, Marquart & Associés (GSM) with elements extracted from studies by Pacific Coach Lines (PCL), Hovey and Associates, and some data from the Neoplan N128 double-deck bus.

The work described in Section 2 resulted in an operational requirement for such a bus based on discussions with inter-city bus operators, and a review of buses with similar operating requirements. In Section 3 each propulsion system element is studied and a system concept developed. Estimates of system performance were made based on reports from current literature and in-house data. In Section 4 the overall bus design concept and system packages are described. Locations of all major subsystems are described and interfaces defined. In Section 5 vehicle performance is estimated and the results are compared to a vehicle with a conventional North American driveline .

The report includes conclusions and recommendations and is supported, where required, by technical data in the form of figures and drawings.

2.0 OPERATIONAL REQUIREMENTS

The operational requirement was derived from a variety of sources, namely discussions with bus operators in Ontario and Quebec, a meeting with Brian Clark of PCL to discuss PCL's double-deck bus requirement, a review of previous work in the area of double-deck bus design by PCL, GSM, and Hovey and Associates, and finally the UTDC R&D data bank. The factors taken into account were speed, range, duty cycle, payload, environmental conditions, ancillary services, noise, reliability, availability, and safety.

The principal concept employed was that of "user-transparency". In other words the hydrogen fuelled bus should have the same characteristics as the baseline diesel bus in terms of payload, range, vehicle performance, reliability, maintainability, refuelling, and driveability. A composite operational requirement was developed from the above sources, which both diesel or hydrogen buses should meet.

It was determined that the requirements are very different from those of an urban-transit bus, particularly in terms of duty cycle. The inter-city bus in current single-deck designs consumes an average of 72,000 litres of diesel fuel a year while covering some 145,000 kilometres. These values are approximately twice those for an urban-transit bus. In addition, the inter-city bus is "energy intensive" and requires a range of 1,000 km, particularly for tour or charter operators. Annual utilization is typically 3,000 hours in the Quebec-Windsor corridor, but less in PCL's environment.

In order to achieve the required quantum leap in driver and vehicle productivity for a high-capacity bus, the desired passenger capacity is in the range 80 to 100. The lower value represents comfortable long distance service with galley and washroom, while the higher value represents shorter, high-density routes such as that of PCL on the Vancouver-Victoria run. The selected values are summarized in Table 1, based on References 1 to 8.

FEATURE	REQUIREMENTS
Speed	Cruise - 100 km/h Maximum - 110 km/h Grade at Cruise speed - 0.9%
Range	1000 km
Duty Cycle	70% @ Cruise Speed 20% @ Low power and Speed 10% @ Idle 3000 hrs. and 145,000 km
Payload	80 to 100 passengers @ 80 kg each Luggage for above @ 20 kg each Freight approx. 4.85 m^3 and 775 kg
Environmental	Altitude 0-1525 m Temperature -35 to +45°C Relative Humidity 5 to 100%
Ancillary Services	Air Conditioning/Heating Compressed Air (Option hydraulics) 24 V DC (Option 110V, 60 Hz AC) Batteries
Noise	80 dBA Maximum Driveaway External 15 m 65 dBA Idle External 15 m 83 dBA Maximum Passenger Compartment
Reliability and Availability	13,000 km between Road Calls 130,000 km minimum per year 15-year Service Life Availability 99.7% Scheduled Maintenance 10% of operating time
Safety	Equivalent to or better than Baseline Diesel

TABLE 1 SUMMARY OF HIGH-CAPACITY INTER-CITY BUS OPERATIONAL REQUIREMENTS

3.0 SELECTION OF VEHICLE SYSTEMS

A complete propulsion system for a bus will consist of the following major systems as shown in Figure 1:

- o Fuel cell and auxiliaries
- o Fuel storage, fuel delivery system and provision for refuelling
- o Power-Conditioning Unit, Motor, and Electrical Auxiliaries.

Each is discussed below.

3.1 Fuel Cell and Auxiliaries

Fuel cells have been studied as a means of propelling a transit bus by UTDC (Refs. 9, 10, 11), by Elenco (12), and by Los Alamos National Laboratory (13, 14). They have also received a great deal of attention as prime movers for automobiles and locomotives. At the time of writing, stationary applications are coming on stream as sources of utility power but apart from isolated examples the only application of fuel cells to date has been the U.S. space program.

A fuel cell in its simplest form consists of an anode and a cathode separated by an electrolyte. Fuel is introduced to the anode and air (or oxygen) to the cathode. With suitable catalysts embedded in the electrodes the resulting reaction generates an electromotive force (e.m.f.) capable of supplying current through an external load. A typical single cell generates between 0.6 and 1.0 volts and from 500 to 1000 amps per sq. metre of electrode surface depending on fuel, oxidant, construction, catalyst, and electrolyte.

The problem areas which have prevented widespread application of this technology as a vehicle propulsion system are related in part to the fuel cell itself, and in part to its system requirements. As shown in Figure 1, in addition to the fuel cell itself, propulsion at the wheels of a vehicle requires:

- o A fuel storage system
- o A fuel delivery system (+ potentially a reformer or cracking unit)
- o An air purification or oxygen storage and delivery system
- o Fuel cell controls and cooling and purging circuits
- o An electrical output control system
- o A motor (+ potentially gearbox).

Fuel cells in general manifest the following drawbacks when compared to conventional drivelines: high cost, short life, and increased weight and volume for given power.

The advantages which have stimulated all the interest and R&D work despite these facts are the fuel cell's much improved thermal efficiency

(typically in the 40 to 60% range) relative to conventional internal combustion engines (20 to 30% range), the potential for use of other than petroleum-based fuels, and very low emissions (15, 16).

The most convenient classification of fuel cell types is by the electrolytes used. These are the following types:

- o Solid Polymer
- o Molten Carbonate
- o Solid Oxide
- o Acid
- o Alkaline.

Each type of fuel cell will be briefly examined with respect to the present application. The solid polymer electrolyte (SPE) cell is characterized by relatively low-temperature operation (80° to 150°C), moderate efficiency (45%), and good power to weight. It has problems, however: the disadvantages of expensive materials and on expensive noble metal catalyst. Moreover, current designs usually use pure oxygen as an oxidant.

The molten carbonate cell, in contrast, operates at a high temperature of 650°C with similar efficiency, but has the advantages that a wider range of fuels and oxidants can be accepted and no noble metal catalysts are required. This type of cell is at an early stage of development and awaits development of corrosion-resistant materials at reasonable cost. A disadvantage in vehicular applications is the slow start-up.

Solid oxide electrolyte cells run at high temperature (1000°C) and exhibit a high efficiency (50% plus), but are probably the least advanced in terms of engineering development. In addition, they are mechanically complex and require high-temperature materials. For vehicle applications the slow start-up is a disadvantage.

Acid and alkaline types have both been tested in prototype vehicles with limited technical success. The acid electrolyte fuel cell has received an increasing amount of attention in the U.S.A. because of the high priority given to methanol as an alternative fuel (methanol would be converted or reformed to hydrogen and carbon monoxide on board). Long life has been demonstrated in stationary applications but a number of disadvantages have surfaced when this cell has been applied to a vehicle. This system requires a noble metal catalyst, and it has low (for a fuel cell) efficiency, typically 40%, a slow start-up of the order of 15 minutes and a poor power-to-weight ratio. Efforts to increase the power-to-weight ratio are compromised by the severity of the corrosion problems and the necessity to use fragile materials.

Given the constraints imposed by the current state of technological development, the leading candidate for vehicular applications in the near to medium term is the alkaline cell.

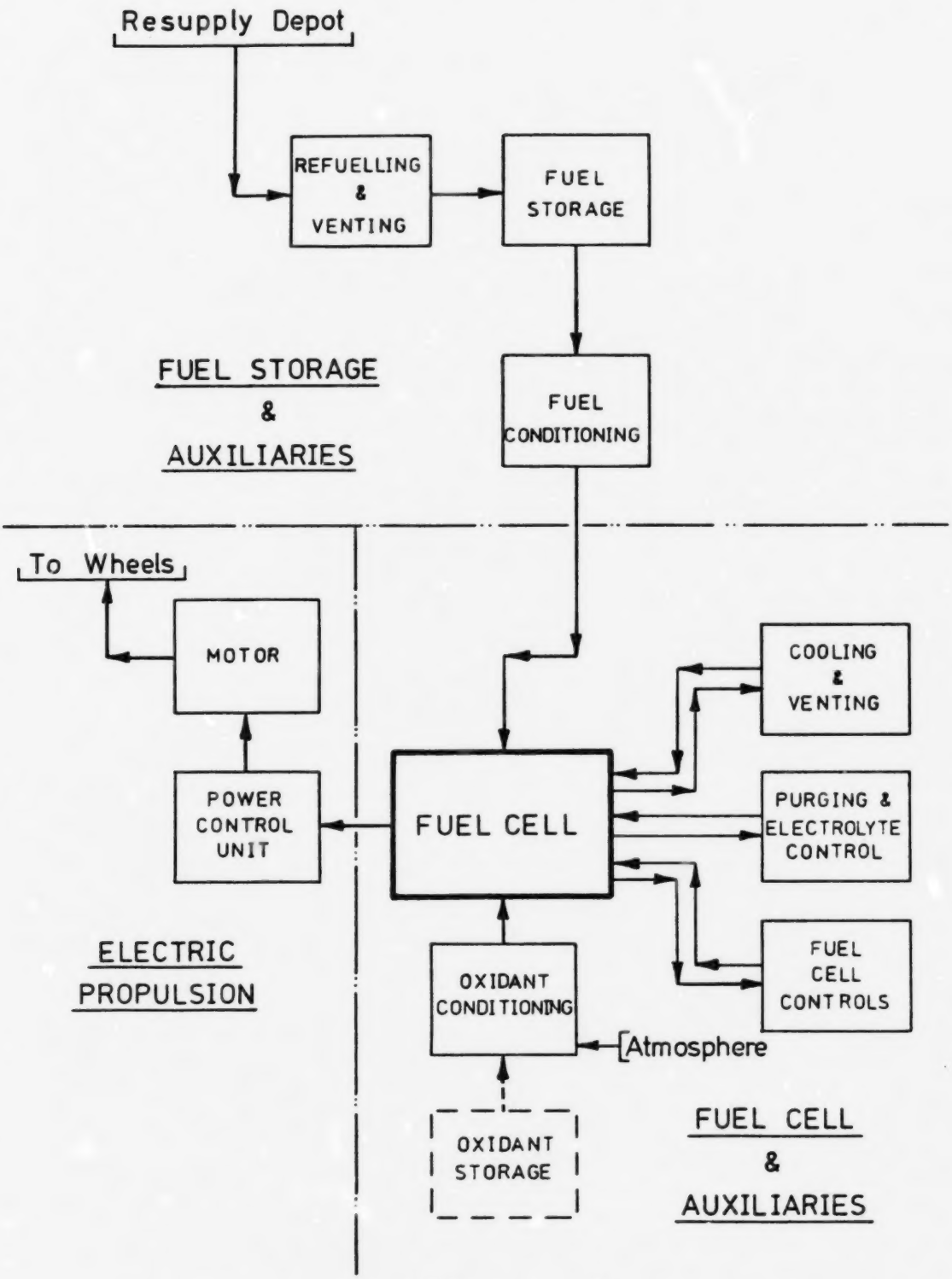

FIGURE 1
TYPICAL FUEL CELL PROPULSION SYSTEM

The alkaline electrolyte power cell has not received as much attention in recent years as the acid cell because of its dependence on pure hydrogen, which is not a constraint on the work reported here. The alkaline cell is characterized by relatively low temperatures (60 to 250°C), rapid start-up (50% power at room temperature immediately), relatively rugged materials, and no emissions.

Catalyst requirements are moderate, and systems have been built with no noble metals in the electrodes. Difficulties to be addressed are the purification of the hydrogen and air streams.

There seem to be no fundamental impediments to developing an alkaline fuel cell system that would achieve a power-to-weight ratio sufficient to allow transit vehicle development. In the long term, the SPE cell, developed for H_2/Air operation, based on more cost-effective technology originally developed for electrolysers (17), is very promising for automotive applications.

Control requirements are discussed in Ref. 11. In terms of fuel supply the fuel cell requires clean gaseous H_2 (preferably electrolytic or LH_2 boiloff). The fuel cell is intended to operate at close to atmospheric pressure and final pressure regulation will require approximately 2 Bars (Absolute) upstream throttling to a nominal 0.01 Bars gauge at the cell. Ideally H_2 temperature would be close to ambient to avoid upsetting cell temperature control.

The air supply might typically be up to 10 times the stoichiometric value at a small ΔP above atmosphere. The air should be filtered and CO_2 reduced in a chemical scrubber from the atmospheric value of 300 ppm down to approximately 10% of this value to prevent excessive build-up of potassium carbonate in the cell and the electrolyte circulation system.

Fuel cell cooling will be achieved by recirculating the electrolyte through a heat exchanger. This will be capable of providing heating for the bus.

In terms of motor control the fuel cell can be considered as a "Replenishable Battery". Feedback from the motor controller is required to increase H_2 feed before the electrode and electrode plenum run out of fuel. The cell has enough capacity or "inertia" to supply several seconds of full current without extra supply of H_2, and can go from "idle" to full power in as little as 3 seconds.

The fuel cell conceptual data is summarized in Table 2.

3.2 Onboard Fuel Storage

A feasibility review (Ref. 19) by UTDC examined the various methods of storing hydrogen on board a vehicle: as a low-pressure gas, as a high-pressure (compressed) gas, as a low temperature (cryogenic) liquid (LH_2), or as a solid or liquid compound of hydrogen. The review

CHARACTERISTIC	VALUE AND COMMENTS
Fuel Cell Type	Alkaline H_2/Air
Efficiency	50% at Cruise
Power Density	0.070 kW/kg Fuel Cell and Auxiliaries 40.0 kW/m^3 Fuel Cell and Auxiliaries
Life	10,000 hrs to 20% Degradation
Air Requirement	Filtered, dewatered (droplets), 90% CO_2 removed (i.e. 300 ppm reduced to 30 ppm)
Fuel Requirement	Electrolytic GH_2 or LH_2 boiloff.
Typical Output	Wide range of Volts versus Amps Trade-offs possible. Typical solution would be series-parallel combination to yield 200 volts/1000 Amps D.C.
Auxiliaries	Air filter, fan, CO_2 scrubber, exhaust, H_2 pressure and flow rate control, vents. Electrolyte recirculation, dumping and heat ex. N_2 Purging. Temperature and pressure controls.

TABLE 2: SUMMARY OF ASSUMED ALKALINE FUEL CELL CHARACTERISTICS: 1983 TECHNOLOGY

eliminated liquid compounds as being either carbon-based or toxic. Corrosive non-fossil compounds such as ammonia and hydrazine would require substantial development work to overcome safety, end-product, and onboard reforming problems. Cryogenic LH_2 was identified as the most promising form for vehicular use. This conclusion is more readily confirmed when the energy storage requirement for the baseline vehicle is considered.

Present methods for the direct storage of hydrogen were examined for an equivalent energy content of 12.0 GJ or 72 Imperial gallons of diesel fuel. The required storage weights and volumes based on current data are tabulated below and illustrated in Figure 2. As indicated, LH_2 offers the only viable method of storage, comparable to diesel in terms of weight and volume required. An inter-city double-deck diesel bus might require two tanks of approximately this size, an urban-transit bus would require only one.

Hydrogen may be stored as a liquid at cryogenic temperatures below 33 K. At a pressure of 1 atm, LH_2 will boil at a temperature of 20.3 K. To store LH_2 for any appreciable time period, a vacuum-insulated cryogenic vessel is essential to adequately minimize heat flow from the outside environment to the liquid. That is, the liquid is contained in an inner pressure vessel (PV) which in turn is surrounded by an outer shell (OS):

- the PV is supported within the OS in such a manner as to minimize the heat conduction paths,
- layers of reflective shields are placed in the space (annulus) between the PV and OS to minimize radiation, and,
- the space is evacuated to minimize both conduction and convection.

A state-of-the-art example of an LH_2 storage tank for vehicular application is the "Beech" design, shown in Figure 3. On the bases of Reference 20, for practical state-of-the-art LH_2 tanks in the size range required for the bus we might expect a weight performance of 34Kg/GJ and a volume performance of 0.215 m^3/GJ.

Cryogenic hardware and techniques are required for the refuelling of LH_2 tanks. A strict procedure of venting, purging, cooldown, and actual liquid transfer must be followed when transferring a cryogenic, inflammable substance such as liquid hydrogen from one container to another. In particular, air must not be allowed to enter the system, and unnecessary vaporization of hydrogen must be avoided as the pressure changes between the refueller and the vehicle tank.

The onboard LH_2 tank must be equipped with a liquid fill line and a vapour vent line, each vacuum-insulated to minimize liquid boil-off and to prevent icing or liquid oxygen condensation on the exterior of the lines. A refuelling connect, comprising two bayonet connectors, would

	FUEL	TANK	PRESSURE	FUEL WT	TANK WT	TOT WT	WT/GJ	FUEL VOL	TOT VOL	VOL/GJ
			atm	kg	kg	kg	kg/GJ	l	l	l/GJ
1.	Diesel	Steel	1	279.3	42.7	322.0	26.83	326.4	343.2	28.600
2.	LH_2	Steel	3	100.0	669.2	769.2	64.10	1534.7	2132.8	177.773
3.	LH_2	Aluminum	3	100.0	340.4	440.4	36.70	1534.7	2132.8	177.773
4.	H_2 (comp)	Steel	150	100.0	6610.4	6710.4	559.20	8196.7	8280.0	690.000
5.	Mg_2NiH_4	Hydride		100.0	4201.5	4301.5	358.46	1357.8	4744.8	395.000
6.	$Mg(Ni)H_2$	Hydride (hi temp)		100.0	2170.8	2270.8	189.23	715.6	2565.6	213.800
7.	$FeTiH_2$	Hydride		100.0	7100.0	7200.0	600.00	1770.5	2742.0	228.500
8.	Microspheres			100.0	906.2	1006.2	83.85	5872.0	6572.4	547.700

TABLE 3
FUEL STORAGE REQUIREMENTS
ENERGY CONTENT = 12.00 GJ

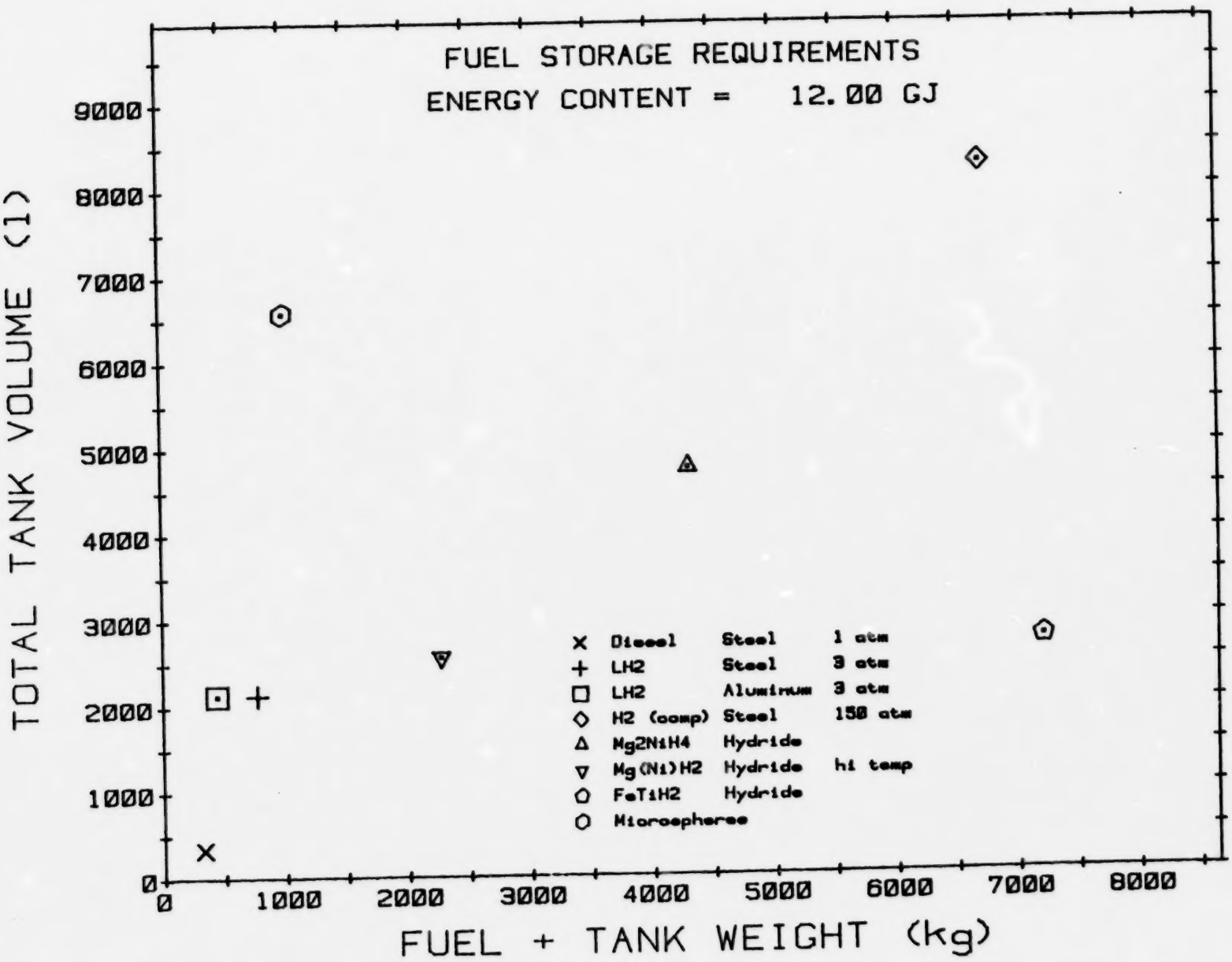

FIGURE 2 - HYDROGEN STORAGE WEIGHTS AND VOLUMES

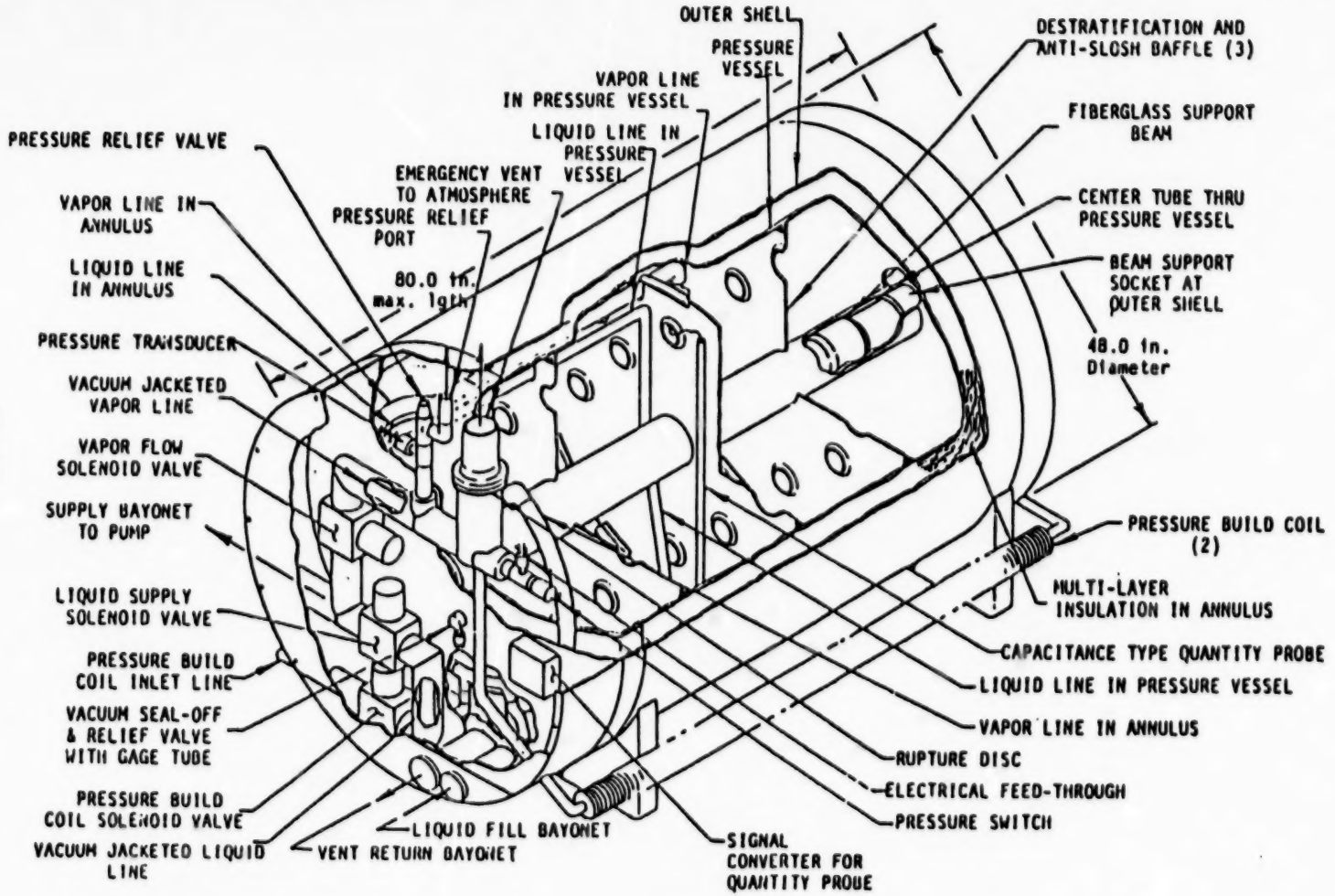

FIGURE 3

CUTAWAY VIEW - BEECH ONBOARD LH2 STORAGE TANK

be required to interface with a liquid hydrogen refuelling station. Standard off-the-shelf cryogenic couplings are available and can be readily adapted.

For the fuel-cell bus, hydrogen is required in its liquid state for storage purposes only. It is recommended that LH_2 be kept within the confines of the onboard storage tank, and that, for the fuel-cell propulsion unit, only hydrogen vapour be withdrawn from the tank, at a maximum rate of approximately 4 grams/sec.

3.3 Electric Propulsion System

Both AC and DC systems were considered for the motive power. DC systems are readily available and have been used extensively in transit propulsion applications. AC systems are a relatively new phenomenon in this field but potentially offer some advantages. AC motors are smaller for the same power output. No commutation problems are encountered (the induction motor), and forced-air cooling is not required. Inverters are about 50% larger than choppers, however, and require a slightly more complex control scheme. For prototype buses, where the centre of interest is the fuel cell, it is suggested that the more conventional DC equipment be selected where reasonable reliability and lower capital costs can be assured.

DC motor control can be accomplished using either a chopper system or a switched resistor controller. Chopper control of DC motors alters the power delivered to the motor by adjusting the applied voltage. Field control can also be performed and, depending on the winding configurations, automatic field control can be implemented so that only the armature current need be chopped. Chopper plus DC motor combinations are generally of high overall efficiency, approximately 85% from electrical input to bus drive axle. Continuous control allows for smooth application of power.

An electric traction system consisting of a DC motor/chopper coupled with an H_2/Air alkaline fuel cell has an overall energy conversion efficiency of between .4 and .45 as supplied to the rear axle. This is considerably higher than a modern diesel engine/transmission combination operating at its peak efficiency point.

Switched resistor control consists of controlling motor currents in and out of the motor circuit. Switched resistors are more wasteful in terms of energy, and efficiencies depend on the route profiles. Power applications are in discrete steps and many steps are required for smooth acceleration. A switched resistor package would be of the same order of weight and size as the chopper but of approximately the same overall efficiency as a diesel system.

Most electric power systems also have the capability for regenerative braking. The fuel cell itself has the capability to transmit power downstream only and cannot store energy. Batteries could

be put in parallel with the fuel cell but this is not an attractive option for inter-city bus duty cycles. In addition, regular bus hydraulic or pneumatic brakes would likely be required as a safety back-up system and no weight gain could be made. Bulky braking power resistors would also be required. Hence, no real advantages are gained with electric braking in this application.

As the motor speeds are comparable to typical diesel shaft speeds, a transmission is not required and the motor could be coupled directly to the rear axle differential via a conventional driveshaft.

A system incorporating a DC chopper with forced air cooling is outlined in Figure 4. Cooling systems are mandatory with most conventional choppers of this power rating. Self-cooled models may become more available in the near future.

Overall power densities are .039 kW/kg and 36.9 kW/m^3.

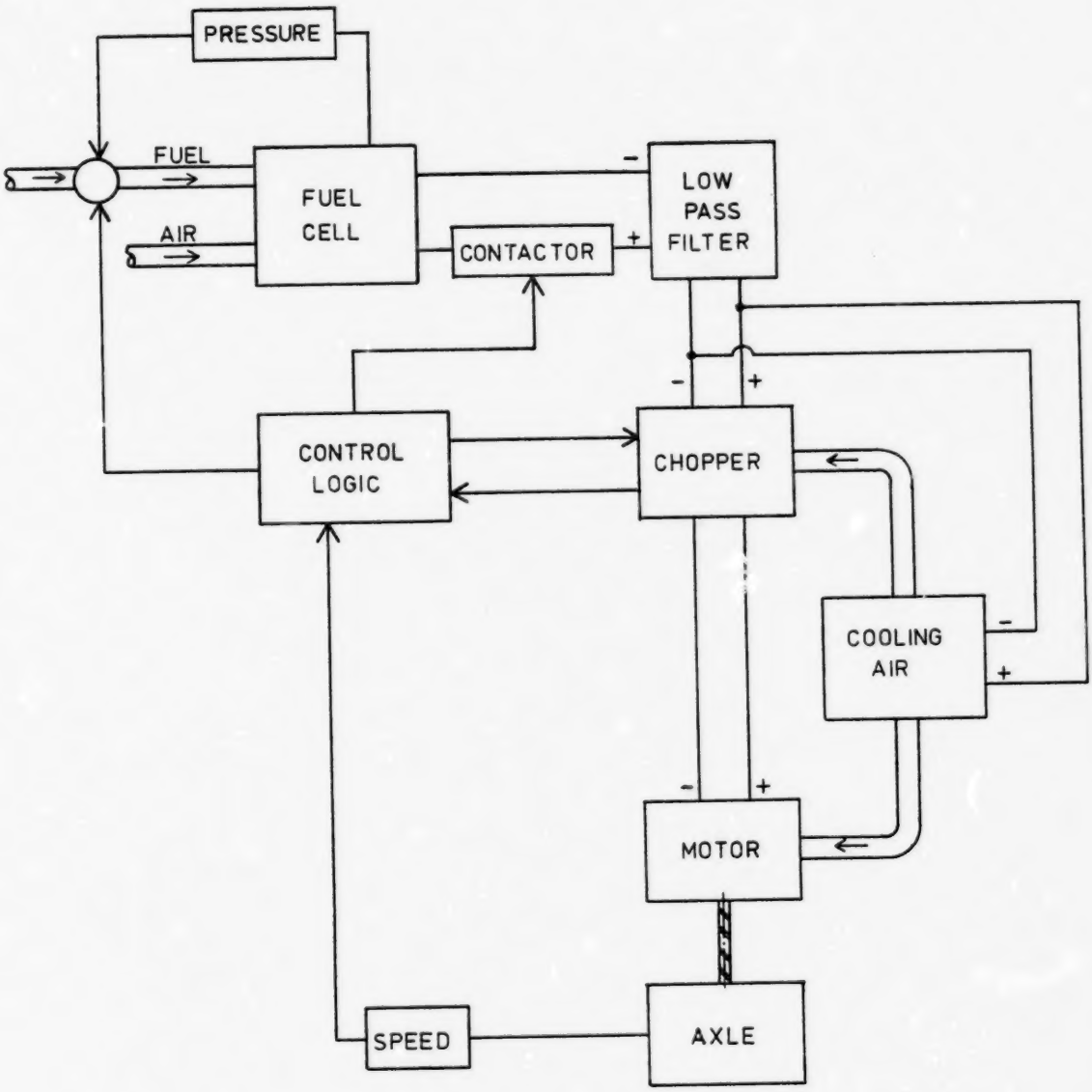

FIGURE 4
ELECTRIC PROPULSION SYSTEM BLOCK DIAGRAM

4.0 DESIGN CONCEPT DESCRIPTION

4.1 Baseline Diesel Vehicle

The baseline diesel vehicle is essentially that proposed in Ref 6, with a length of 14 m (46 ft), a width of 2.59 m (8ft 6ins), and a height of 4.12 m (13 ft 6 ins). When configured for inter-city operation, with a relatively generous 800 mm seat spacing, it has a capacity of 81 passengers, luggage volume of approximately 8.27 m^3 and freight volume of 4.85 m^3. The Gross Vehicle Weight (G.V.W.) would be approximately 23,000 kg with a tare weight of 14,000 kg (Ref. 21). The power required for cruise on level ground at 100 kph is 202.5 kW at the flywheel, and to climb a 0.9% grade at that speed 272.5 kW are needed. If we include auxiliary loads we require a nominal 295 kW (390 Hp) powerplant.

This vehicle has been assumed to have an aerodynamic drag coefficient of 0.6, which should be relatively easy to achieve, and to travel the necessary 1000 km, a fuel tank of 150 Imperial Gallons (25.2 GJ energy) is needed.

4.2 Evolution of Fuel-Cell Bus Concept

The new propulsion system elements are both bulkier and heavier than the diesel system that is being replaced. The design philosophy employed, followed the steps outlined below:

- Removal of existing propulsion system
- Estimate of New Gross Vehicle Weight
- Revisions to initial estimated system weights and volumes based on new weight, including structural provisions for increased weight (This included re-selection of wheels, tires and axles if required.)
- Iteration to determine final vehicle weight
- Conceptual layouts to establish feasibility of arrangement and location of major added systems
- Second-order refinement of propulsion system weight and volume breakdowns
- Check of new vehicle performance, weight distribution, passenger and luggage capacity, etc.
- Final conceptual layouts of fuel-cell high-capacity bus.

During this process it was rapidly discovered that the principal problems to be overcome were volume constraints and weight distribution constraints rather than weight itself. Layouts with single and dual fuel tanks were attempted and the systems distributed in various

locations around the bus. The final concept is discussed in Section 4.3.

4.3 Fuel-Cell High-Capacity Bus Concept

4.3.1 General

The most practical configurations had the following basic layout:

- Motor between trailing rear wheels driving forward.
- Power-Conditioning Unit and Auxiliaries behind rear axle at low level with control panel and diagnostics above rear bumper.
- Fuel tank(s) at rear of bus above Power-Conditioning Unit
- Fuel cells in two virtually self-contained stacks, one above each front wheel arch.

Proposed layouts for single and dual LH_2 storage tanks are shown in drawings 58-5501-001 and -002 which form Appendix A.

4.3.2 System Descriptions

The fuel cell will have an output of 245 kW for the cruise condition, and a peak rating of 330 kW for grade climbing and acceleration. This will require a total volume of 6.125 m^3 and the fuel cell and auxiliaries will weigh 3500 kg. Two virtually independent fuel cells will be used, thus providing "get home" capability at reduced power. The fuel cell will operate at atmospheric pressure and 60°C. The fuel cell stacks themselves will weigh 2100 kg and are rectangular in shape. The auxiliaries can be arranged more easily into an irregular volume.

The fuel storage system will consist of dual tanks mounted horizontally at the rear of the bus with one tank above the other. This enables a better allocation of space on the upper deck. From a cryogenic engineering point of view, the single tank layout was preferred. All control valves and safety valves are mounted within a sealed shroud at one end of the tanks. The tank space is sealed from the rest of the bus by an insulated firewall, and well ventilated to the atmosphere. The refuelling fill and vent connections are located on the right-hand side of the bus, behind and above the rear wheels. The heat exchanger and receiver are located in the same compartment as the storage tank. A fuel line containing low-pressure (2 to 3 bar) ambient-temperature hydrogen runs forward to the fuel cells.

The electric propulsion system is mounted where the original diesel propulsion system would be fitted, in a cradle for easy removal. Diagnostic equipment and instrumentations are mounted at the rear of the bus behind an access panel for easy maintenance.

The system characteristics are summarized in Table 4. A more detailed weight breakdown for the conceptual design is given in Table 5.

CHARACTERISTIC	VALUE	COMMENT
SPEED	100 km/h Cruise 110 km/h maximum 0.9% Grade at Cruise	Top Speed gearing limited. Power available for 117 kph.
RANGE	1,000 km	17.0 GJ storage requirement is 67.5% of Diesel Baseline.
PAYLOAD	79 passengers 79 x 20 kg luggage 640 kg freight	Slightly reduced payload relative to 81 passenger baseline.
WEIGHTS	Tare 19,800 kg GVW 28,400 kg Front/Rear 45%/55%	24% increase in GVW over baseline. Axle load limits are difficult to meet.
DIMENSIONS	Length 14 m Width 2.59 m Height 4.115 m Wheelbase 7.62 m	Exceeds current rigid vehicle limits in length. Height and width legal.
POWER	Propulsion: 225 kW cruise 310 kW maximum Accessories: 20 kW	-

TABLE 4
MAJOR CHARACTERISTICS OF FUEL-CELL INTER-CITY BUS

ITEM	WEIGHT KG
TARE WEIGHT LESS PROPULSION SYSTEM AND 2 SEATS	11,485
FUEL CELL STACKS	2,100
FUEL CELL AUXILIARIES	1,400
POWER-CONDITIONING UNIT AND AUXILIARIES	1,730
MOTOR	890
FUEL STORAGE TANKS	438
FUEL	142
REFUELLING SYSTEM, PIPING. VENTS	90
INCREASED STRUCTURE, FIREWALLS, INCREASED WHEELS, ETC.	1,525
REVISED TARE WEIGHT	19,800
79 PASSENGERS @ 80 kg	6,320
LUGGAGE @ 20 kg	1,580
FREIGHT $4m^3$ @ 160 kg/m^3	640
DRIVER	80
REVISED GROSS VEHICLE WEIGHT	28,420 kg (28,400)

TABLE 5: FINAL WEIGHT BREAKDOWN - FUEL-CELL BUS

5.0 ASSESSMENT OF BUS PERFORMANCE

In this section the performance of a fuel-cell bus is assessed in comparison with a diesel-powered bus. It has already been determined in the previous section that the fuel-cell bus will match the baseline vehicle in speed, acceleration, and range. The critical differences are discussed below, together with an assessment of expected future performance improvements.

5.1 Energy

Although the fuel cell bus is 24% heavier than the equivalent diesel vehicle, the energy consumption is only 67.5% of that of the diesel bus. If we allow for the energy required to liquefy the hydrogen in presently practicable plants, this advantage is reduced to approximately 90% of the diesel baseline.

In stop- and go-traffic the improvement would be greater because the part-load efficiency of the fuel cell is even greater relative to the diesel engine's, reaching 60% near idle.

5.2 Payload

The principal loss in transportation efficiency is the loss of payload. The number of passengers is reduced from 81 to 79. A higher-density bus with a length of 15 m configured for operation on the Vancouver-Victoria run would not feature a galley or toilet. In this version the payload would be reduced by the same number of passengers-from 97 to 95. However, volume would be sacrificed in the freight compartment (4.85 m^3 down to 4.1 m^3) and luggage compartments. More specifically the walk-on luggage area above the front wheel wells would be lost.

In review by GSM and PCL it was noted that the fuel-cell bus had lost an amount of payload that was significant in economic terms for high-density routes, and that the forward view and general visibility on the lower deck were impaired relative to the baseline configuration (without baggage).

In summary, a current fuel-cell propulsion system will occupy approximately 13.8 m^3 within the envelope of the bus, resulting in a net loss in revenue-generating payload volume of 6.9 m^3.

5.3 Driveability and Operability

The electric propulsion system offers the possibility of extremely smooth and vibration-free operation, with low internal and external noise levels. In common with many electric-traction transit systems, it makes it relatively simple to incorporate spin-slide sensing and control of the drive axle and jerk limiting during onset of acceleration. Use of the alkaline fuel cell will allow start-up and driveaway within a

length of time (5 minutes) considered normal for this class of equipment. The refuelling and vent system has been sized to allow refuelling in less than 5 minutes, which closely approaches the minimum 3 minutes required for inter-city buses.

To allow operation in some restricted locations (e.g. potentially ferries), a means of venting must be developed which either converts excess GH_2 to electricity in the fuel cell, or catalytically burns the GH_2 at low temperature. It must be stressed that venting is not normal operation, and would be required only after considerable parking periods with no fuel use, of the order of 36 to 48 hours.

5.4 Safety

Hydrogen is frequently perceived as a dangerous substance; however, numerous studies and lengthy practical experience (22, 23, 24) have determined that hydrogen is not necessarily more dangerous than, but merely different from, the fuels to which we have become accustomed. All propulsion systems with mobile energy storage (e.g. flywheels, batteries, fuels, hydraulic pressure) by definition could release energy at an uncontrolled rate in the event of some incident. Features of hydrogen which are favourable in an accident are the strong double-walled construction of the dewar, the rapid dissipation of gaseous hydrogen upwards and away from the scene, the rapid boiling and disappearance of cryogenic LH_2, its high ignition temperature, and the low amount of radiated heat if it is ignited. Its unfavourable features in comparison to diesel fuel are the ease of ignition by electrical short or static spark, a slightly higher flame temperature, and a rapid rate of combustion. If confined, hydrogen-air mixtures can explode in some circumstances. The conclusion is drawn that a hydrogen-fuelled vehicle could be engineered to meet or surpass current transit vehicle safety standards.

5.5 Cost

With the current status of fuel cell development for mobile applications, it is impossible to determine the operating costs associated with the fuel cell itself in terms of its maintenance and replacement cycle. However, capital costs for the system are more readily estimated. In addition, LH_2 storage systems and electrical propulsion machinery are characterized by long life and very low maintenance. It is anticipated that the "no moving parts" aspect of fuel cells will eventually result in long life and low maintenance requirements.

For the fuel-cell bus concept developed in this report the following figures represent approximate costs with small production quantities (less than 5):

Basic Vehicle	400,000
Less Diesel System	-40,000
Fuel Cell and Auxiliaries	150,000
Electric Propulsion	150,000
Fuel Storage and Auxiliaries	85,000
TOTAL ($ CAN. 1983)	745,000

It should be noted that if LH_2 were available at a price competitive with diesel it would take an unreasonable length of time (approximately 90 years) to pay back the initial investment in more energy-efficient propulsion machinery. However, estimates made by Elenco indicate a reduction in cost for fuel cells of 50% by the year 2000, and for the electrical propulsion of at least 10%. The fuel storage system is highly sensitive to production volume; a cost of less than $20,000 is readily attainable. This would reduce the capital-cost of the fuel-cell bus to $590,000.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions were derived from the work:

- The major conclusion is that in the context of a high-capacity inter-city bus, the LH_2/Fuel Cell/Electric propulsion system is both feasible and promising.

- Use of technology which is either immediately available or foreseeable with only modest incremental improvements by 1985 results in a fuel-cell inter-city bus which, when compared to a diesel-powered baseline vehicle:

  - Consumes 67.5% of the energy per seat per km
  - Achieves identical range, speed and acceleration
  - Has slightly lower passenger seating (less by 2.5%)
  - Loses 33% of the baggage volume
  - Loses 15% of the freight volume
  - Is 24% heavier
  - Costs almost double the baseline vehicle cost in small (less than 5) production volumes.

- Presently foreseeable technology improvements will in the 1990 to 2000 time frame achieve the following:

  - Halve the cost, weight and volume of the Fuel Cell
  - Halve the weight and volume and slightly reduce the cost of the electrical propulsion system
  - Drastically reduce LH_2 storage system costs to 25% of prototype values.

It is expected that taken together the loss in payload will be virtually restored by the year 2000, and further energy use reduction relative to the diesel baseline will be achieved.

6.2 Recommendations

In order to achieve some of the predicted performance improvements, and to bring the propulsion system closer to potential demonstration and implementation, further work is recommended in the following areas:

- The Solid Polymer Electrolyte fuel cell is worthy of further investigation based on recent activity in this area.

- The potential for performance improvements (particularly in volume) of the alkaline cell via pressurization and higher-temperature operation should be investigated.

- More detailed structural layouts are required for the next iteration of design.
- Small (under 15 kW) fuel cells of the alkaline type should be tested in a realistic mobile application.
- Development of the full-scale (approx. 100 kW) fuel cell for the Elenco Trolley Bus should be monitored.

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HYDROGEN FUEL CELL

FOR

HIGH CAPACITY BUSES

APPENDIX "A"

TO

FINAL REPORT

Prepared for the

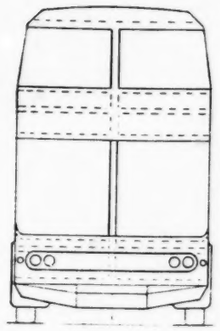
Transport Canada

Transportation Development Centre

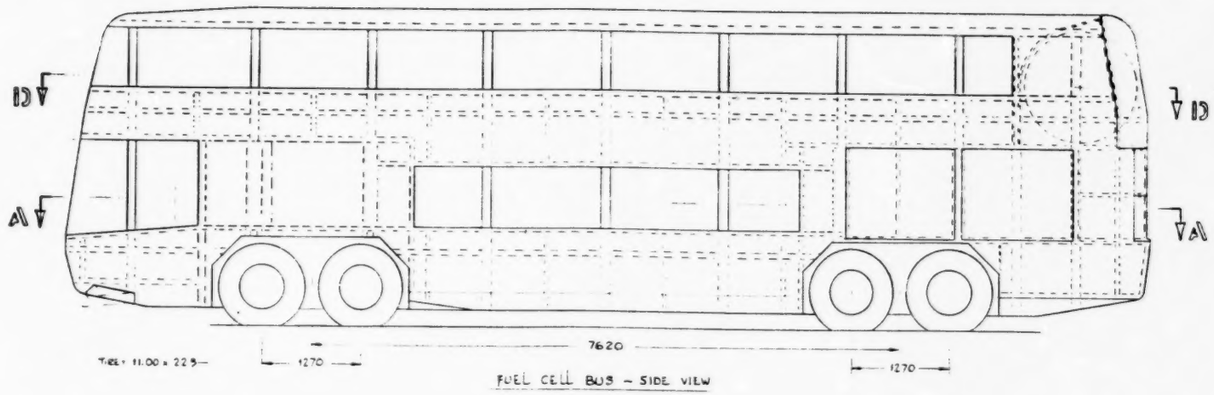
Contract No. 4932/4321

UTDC RESEARCH & DEVELOPMENT LTD. REPORT NO. 585000

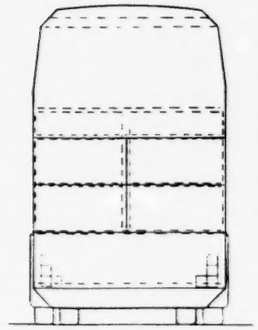
DATED: 30 JUNE 1983



FRONT VIEW



FUEL CELL BUS - SIDE VIEW



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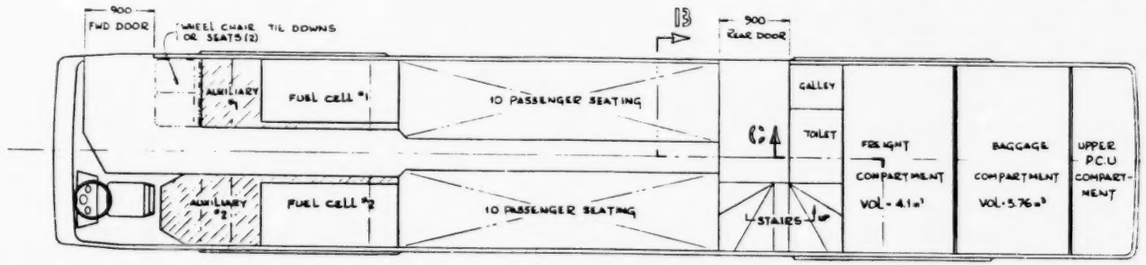

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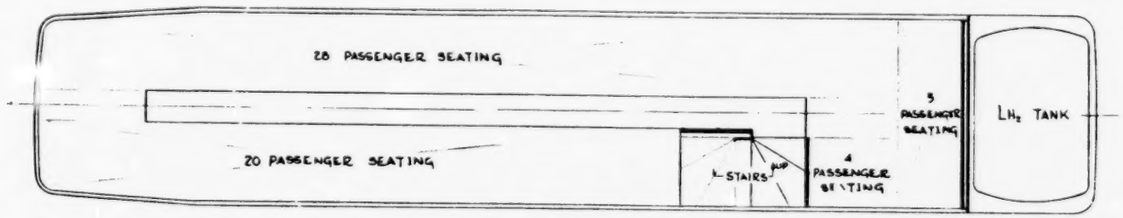

D-D VIEW LOOKING DOWN ON UPPER DECK

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PROJECTION	SCALE 1:25	SHEET 1 of 2

FUEL CELL BUS (PROPOSAL #1)
11.00 x 22.5 TIRES & SINGLE TANK

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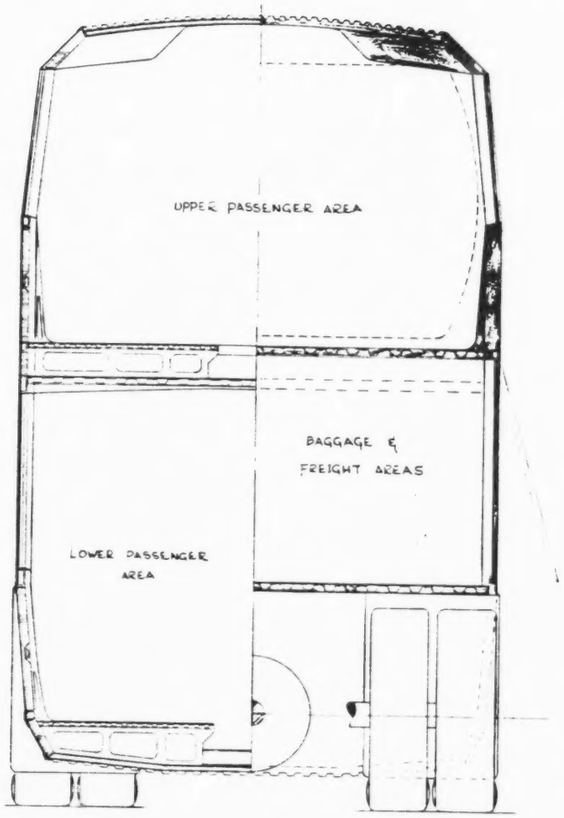
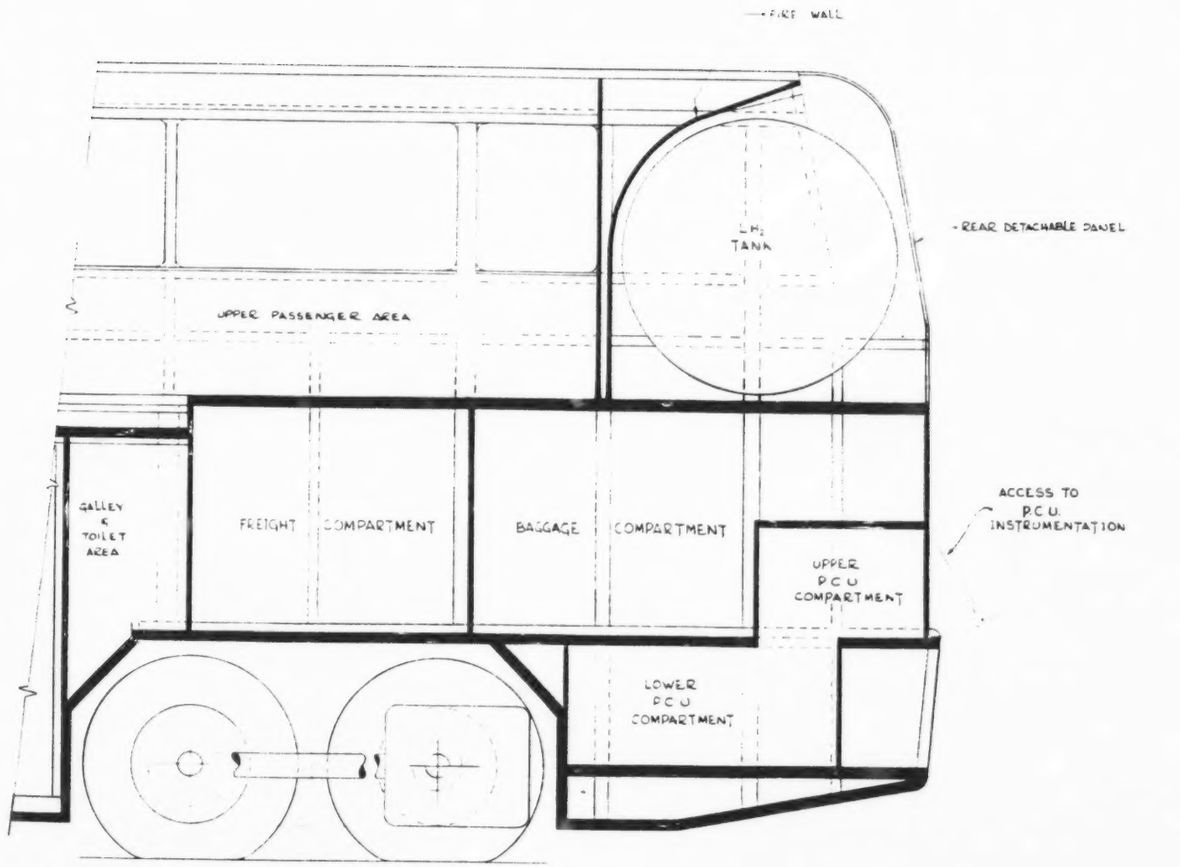


VIEW ON 13-13



VIEW ON C-C

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ALL DIMENSIONS IN MILLIMETRES	
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FUEL CELL BUS (PROPOSAL #1)
11.00 x R22.5 TIRES & SINGLE TANK

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SCALE 1:10	SHEET 2 of 2	

REVISIONS				
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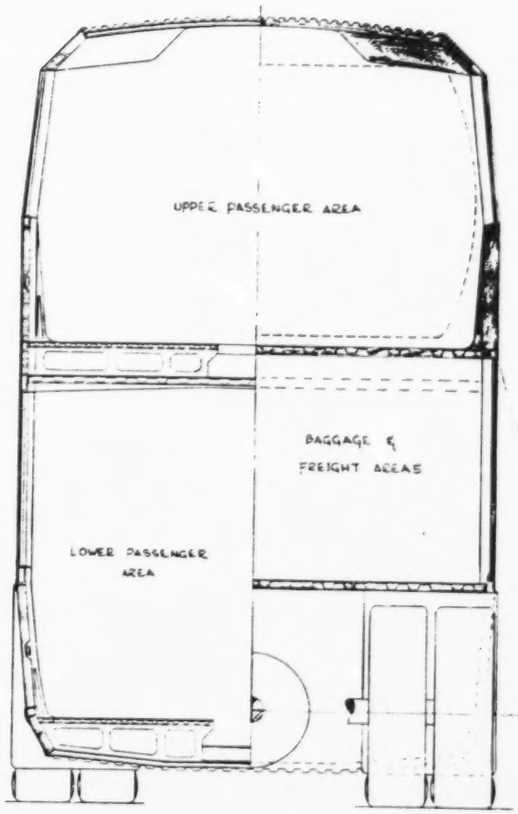
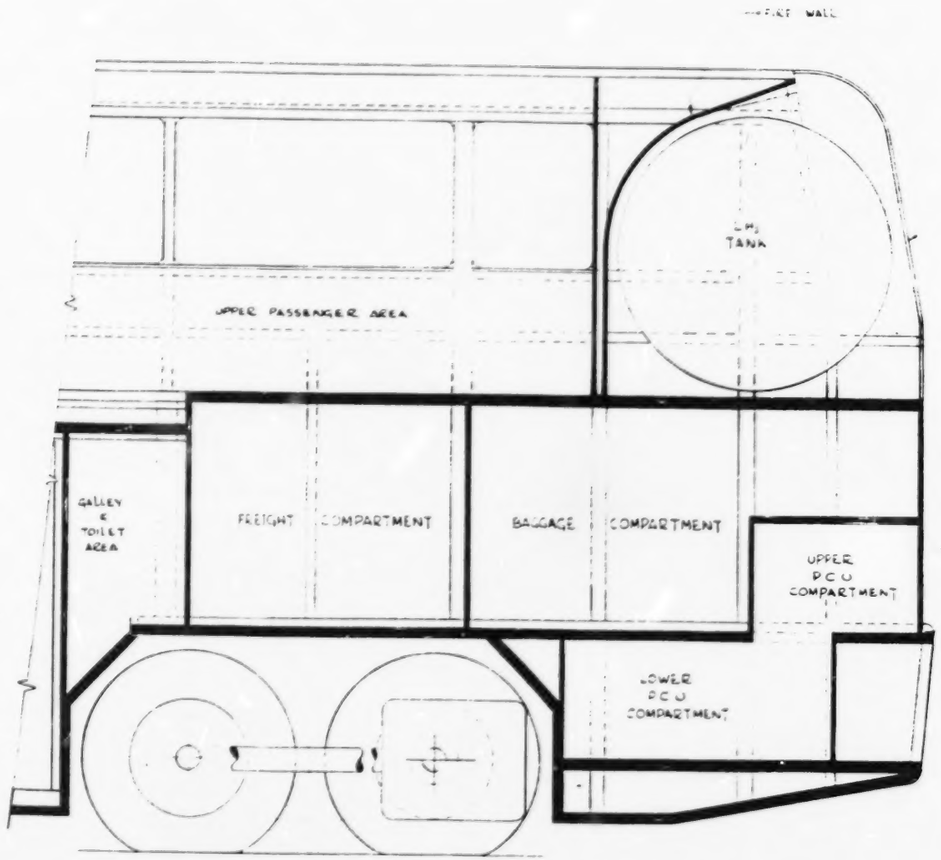


VIEW ON B-B



VIEW ON C-C

FUEL CELL BUS (PROPOSAL #1)
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DWG NO 58-5501-001
SCALE 1:10
SHEET 2 of 2

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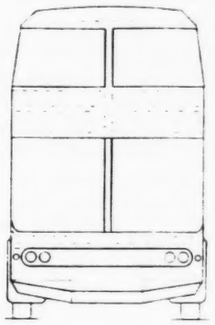
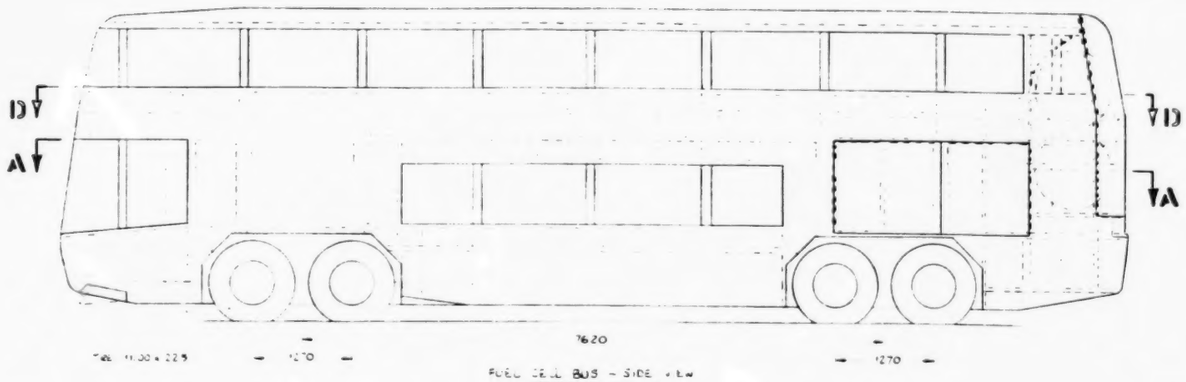
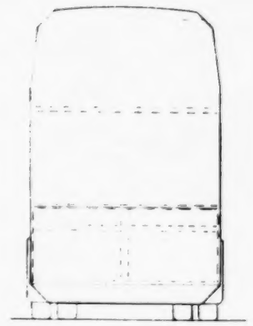


FRONT VIEW



FUEL CELL BUS - SIDE VIEW



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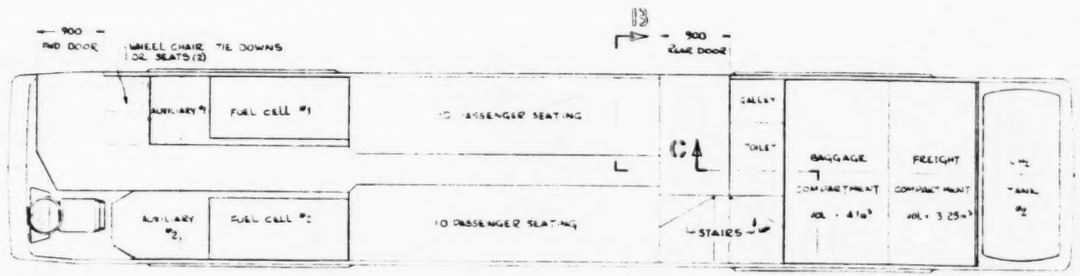

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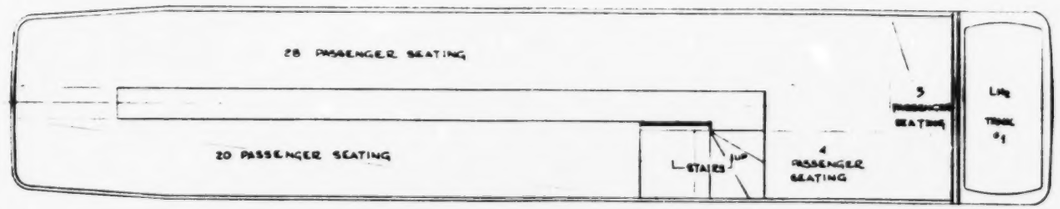

B-B VIEW LOOKING DOWN ON UPPER DECK

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	SCALE 1:25	SHEET 1 of 2

FUEL CELL BUS (PROPOSAL "2"
11.00 x 22.5 TIRES & DUAL TANK
58-5501-002

REVISIONS			
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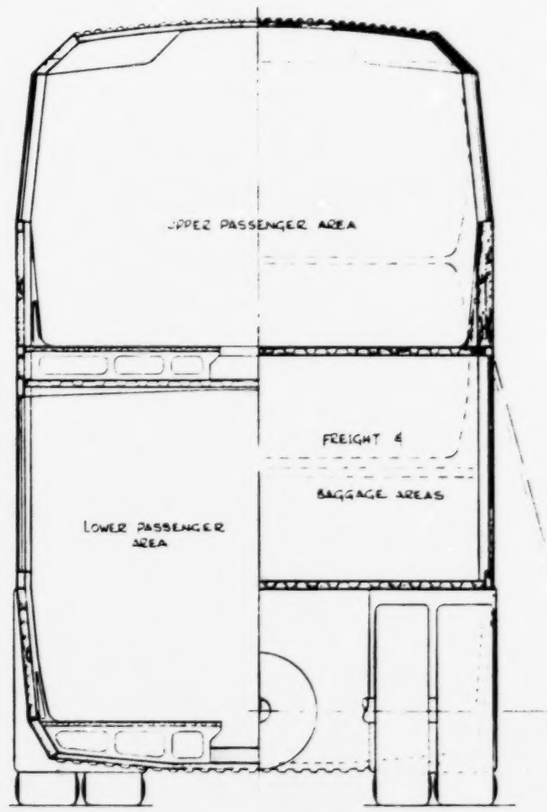
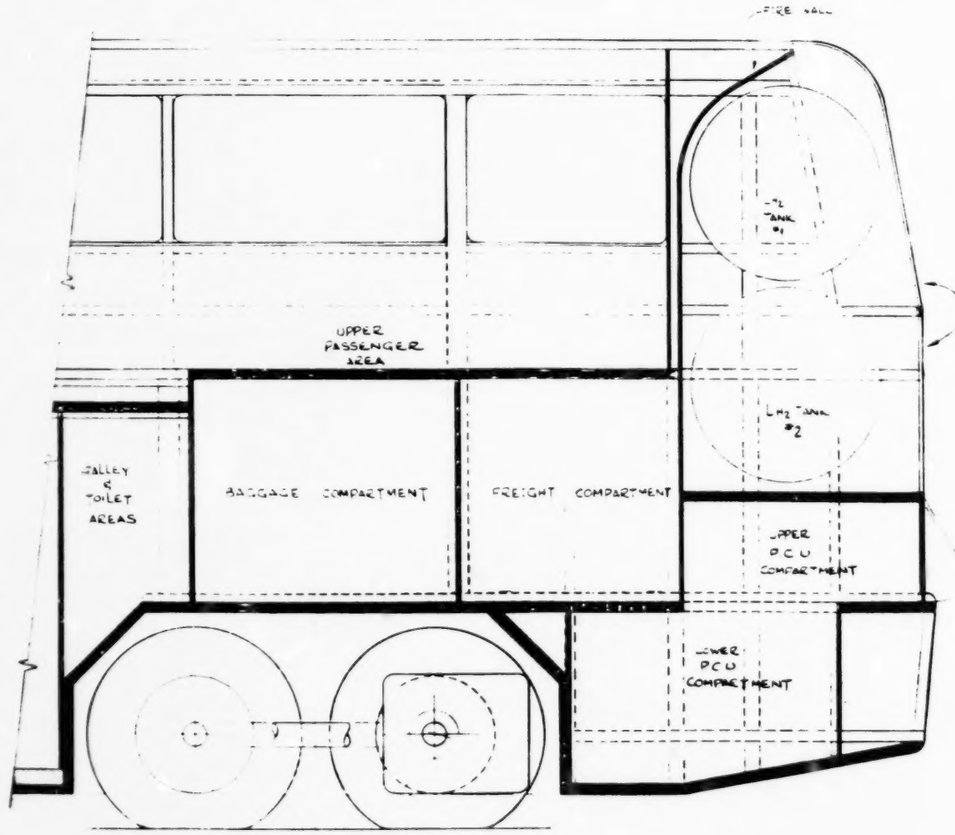


VIEW ON B-B



VIEW ON C-C

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FUEL CELL BUS (PROPOSAL #2)
H 600 X 22.5 TIRES & DUAL TANK

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POOR

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